



AWD Torque Vectoring

Combined Advanced Vehicle Dynamics

ACHA6011

Mark Sandford

By Evan Morcom (1802426)

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1.0 - Introduction

The vehicle the report has been resolved around the Ferrari FF which was released in March 2011 and was also Ferrari's first all-wheel drive vehicle. The main focus is analysing Ferrari's first all-wheel drive system and further understanding the impacts on vehicle dynamics and potential control strategies from the torque vectoring system. Ferrari's main point when advertising this car is the 4WD torque vectoring system underneath the bodywork, Ferrari greets the reader on the FF land page with:

A four-seater that utterly changes the whole GT sports car concept, hailing nothing short of a revolution in the automotive world. Even the most cursory glance at the FF's sleek, Pininfarina-penned super model profile will tell you that. Drive it - anywhere, anytime, in any weather or road conditions (Ferrari, 2011)

2.0 - Ferrari FF 6.2 V12

- Power: 486kW at 8000RPM
- Torque: 683Nm at 6000RPM
- 0 – 60mph: 3.7 seconds
- Transmission: 7 speed DCT Gearbox with 4RM
- Wheelbase: 2990mm
- Kerb Weight: 1880kg
- Weight Distribution: 47% Front – 53% Rear
- Front tyre size: 245 35 20
- Rear tyre size: 295 35 20



Figure 1 - Ferrari FF 6.2 V12 (Ferrari, 2011)

3.0 - Torque Vectoring Systems

Torque vectoring systems are designed to improve a vehicles grip whilst driving in changing conditions and or driving at speed whilst also still keeping normal functionality of the vehicle when driving in a normal manner.

Torque vectoring systems are controlled by a computer onboard the vehicle which regulate how much power the vehicles motor or engine transmits to each individual wheel. As the power each wheel receives, the grip that can be achieved is higher than a conventional manual system and also allows a vehicle to accelerate at a faster rate without breaking traction. Though the method of monitoring and applying the power can be done mainly in two different techniques, either by using a differential or using the braking system. (Hirons, 2022)

Using the braking system isn't as commonly seen within the automotive industry but some chassis like hot hatchbacks don't allow the use of a differential used for torque vectoring due most being small and compact. It would be possible in some cases to use a differential however from a costing perspective, the manufacturer will most often or not use the braking system.

Torque vectoring through brakes is a much less mechanically complex system compared to the differential method, the system operates on purely by applying the brakes which ever corner necessary, this allows for more power from the input to be transferred to the wheels that aren't being held by the brake which will have more grip will in turn, result in an improvement in the cars rate of rotation and acceleration during and after the corner. (Hirons, 2022)

Torque vectoring by using a differential is a much more complex mechanism compared to the brakes, it shares similarities with an open differential with the adjustability to become a limited slip differential (LSD) or the possibility of a spool differential if the manufacturer allowed the controlling computer however both an LSD are is a primarily mechanical reactive system that work in definite scenarios to limit the amount of slip from a particular wheel, there are different types of LSD, all working with different internals ending in different slip rates and ramp effect. A spool differential is both wheels locked together always rotating at equal speed regardless of grip level. The opposite end of differentials are open differentials. An open diff allows for relative speed difference of the wheels, the open diff forces the torque to be equal in both half shafts however the torque cannot be supplied but only demanded or resisted.

The torque vectoring systems using the differential combine the open differential with a pack of multi-plate clutches on either side, together with sensors measuring the wheel speed,

pitch, and the yaw of the car. The clutches are not always engaged and are instead electronically- or hydraulically actuated.

When the clutches are inactive the car functions as a conventional vehicle with an open differential, with wheels rotating at different speeds through a turn to prevent skidding.

If one (or both) of the clutch packs are active, they work to multiply or reduce the torque being directed to a wheel. In situations such as a hairpin turn, this helps the driver rotate the car by increasing the amount of torque being sent to the outside wheel.

If the car is travelling in a straight line, the clutch packs are deactivated and the car retains the characteristics of an open differential, with torque being distributed evenly between the wheels for greater stability. (Shah, 2020)

4.0 - A lumped mass model of the vehicle

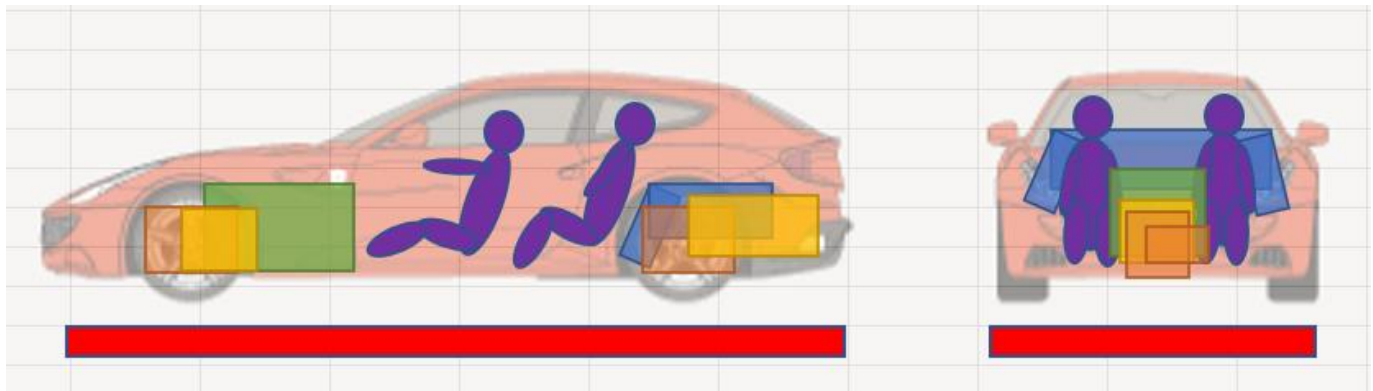


Figure 2 - 2D Render of FF with Lumped Mass Model (Outlines, 2011)

As Ferrari is renowned for being quiet difficult to find data for the cars, the mass from the gearbox has been assumed from other manufacturers 7 speed dual clutch transmission gearboxes. The BMW 7 speed DCT gearbox has a mass of 80kg (SLG, 2021) though BMW mostly has their gearboxes attach to the rear of the engine via a bell housing, as Ferrari places there 2nd gearbox on the rear axle, the bell housing is not needed, and some mass can be deducted from that assumption. The mass used for the 2nd or rear gearbox was 72kg. The Power Transfer Unit (PTU) which is affectively the front gearbox and using only two forward speeds and a reverse. The mass for the PTU wasn't found and the assumption was made of 40kg. The two gearboxes can be seen as yellow boxes on the lumped mass model.

The differentials are built in within the gearbox assembly so finding an exact mass for these units was proven a challenge to find a mass value for both differentials used in the FF. The differentials are represented by the orange boxes. A regular LSD weighs roughly 25-30kg so with the added extras of the motor and wet clutches, the assumed mass used is 50kg for both differentials.

While struggling to find an absolute mass value for the FF 6.3L V12 engine , the engine from the Ferrari 312T mass is 175kg and the Ferrari 250 engine has a mass of 173kg, both engines being V12's, the assumption of the FF engine being 175kg was made. The green box on the lumped mass model represents the engine. (AdjustMyCar, 2013)

Blue = fuel tank (91L) The fuel tank is represented by the blue shape on the diagram, as the tank holds 91L of fuel and petrol roughly weighs 740g a litre, the mass used on the fuel tank 67kg rounded. (Cottingham, 2015)

As the Ferrari FF can seat 4 passengers and the global average body mass is 62kg, the total passenger mass across the two purple drawings on the lumped mass model is 248kg. (Rettner, 2013)

5.0 - Longitudinal Centre of Gravity Position

As the Ferrari FF mass, wheelbase and weight distribution is known, calculating the longitudinal centre of gravity can be done quite easily. Working from the front axle, the mass acting on the front wheel will be the total mass multiplied by the percentage of front weight distribution.

$$\text{Front Axle Mass} = \text{Total Mass} \times \text{Percentage of front weight distribution}$$

$$\text{Front Axle Mass} = 1880 \times 0.47$$

$$\text{Front Axle Mass} = 883.6 \text{ Kg}$$

From this, the longitudinal centre of gravity can be calculated from taking the opposing rear weight distribution multiplied by the wheelbase.

$$\text{Longitudinal C of G} = \text{Wheelbase} \times \text{Percentage of rear weight distribution}$$

$$\text{Longitudinal C of G} = 2990 \times 0.53$$

$$\text{Longitudinal C of G} = 1584.7 \text{ mm}$$

The longitudinal centre of gravity position is 1584.7mm from the front axle, this would be it is 1405.3mm from the rear which indicates the Ferrari FF longitudinal centre of gravity is towards the rear of the car, this can be expected due to have the rear gearbox behind the rear axle, shifting that weight distribution backwards.

Due to physically not having the vehicle, calculating the vertical height centre of gravity position is difficult however using some assumptions, an approximate height can be created.

The method if the car was present would have been to firstly measure the height of the centre of the wheel hub, the mass and longitudinal location is already known. At the point the rear of the vehicle would be lifted to create forward pitch and then the mass acting on the front axle would be re-measure and the angle of which the vehicle is pitched would now be measured. Using the formula below the CG height can be calculated

Where,

RF & RR = Hub heights

W = Total Mass

L = Wheelbase

a & b = longitudinal position CG

θ = angle of tilt

WF = Front axle mass once tilted

$$CG_{Height} = R_F \left(\frac{a}{l} \right) + R_R \left(\frac{b}{l} \right) + \left(\frac{W_F l - W a}{W \tan \theta} \right)$$

As the Ferrari uses a front tyre of 245/35/20 and a rear tyre of 295/35/20, the hub heights can be found by dividing the diameter by 2. The front hub height is 340.5mm and the rear is 357mm from the ground.

Since the car hasn't been tilted, the mass acting on the front axle once tilted will be an approximation. Since the regular mass is 1880kg and the standard weight distribution is 47% to the front, the approximation has been made that if the car has been tilted 20°, the mass will be 1000kg.

$$CG_{Height} = 340.5 \left(\frac{1405.3}{2990} \right) + 357 \left(\frac{1584.7}{2990} \right) + \left(\frac{1000 \times 2990 - 1880}{1880 \tan(20)} \right)$$

$$CG_{Height} = 857.9mm \text{ (Approx.)}$$

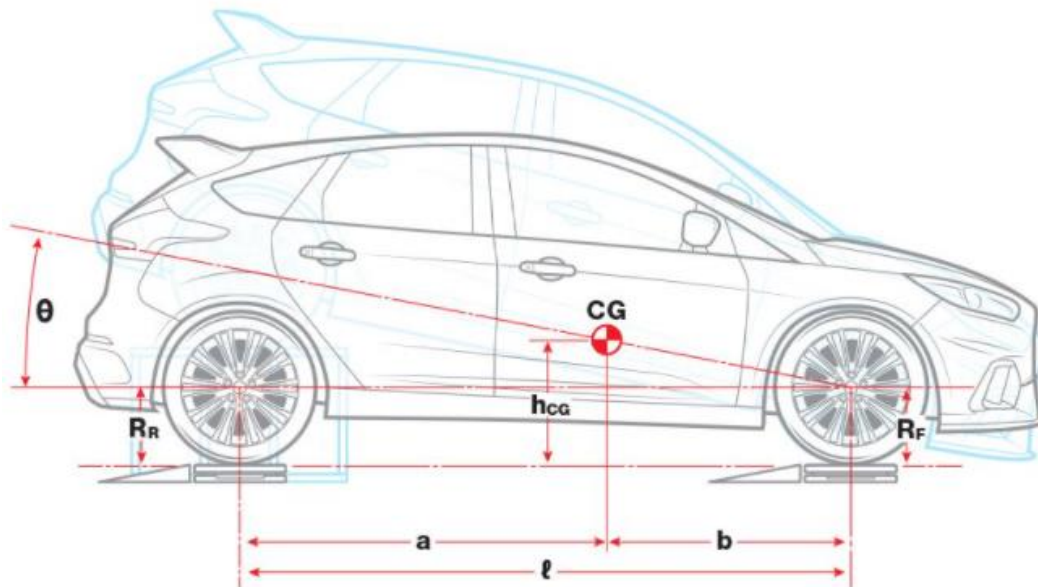


Figure 3 - CG Height Labelled over Focus RS (Car and Driver, 2018)

6.0 - FF Moment of Yaw Inertia

The Ferrari FF's moment of inertia calculated will not be what Ferrari states only the major components having a large impact on the inertia value in the ZZ axis (yaw) was considered. This consisted of:

Engine X1

Gearbox X2

Differential X2

Occupants X4

Fuel Tank X1

Wheels and Tyres X4

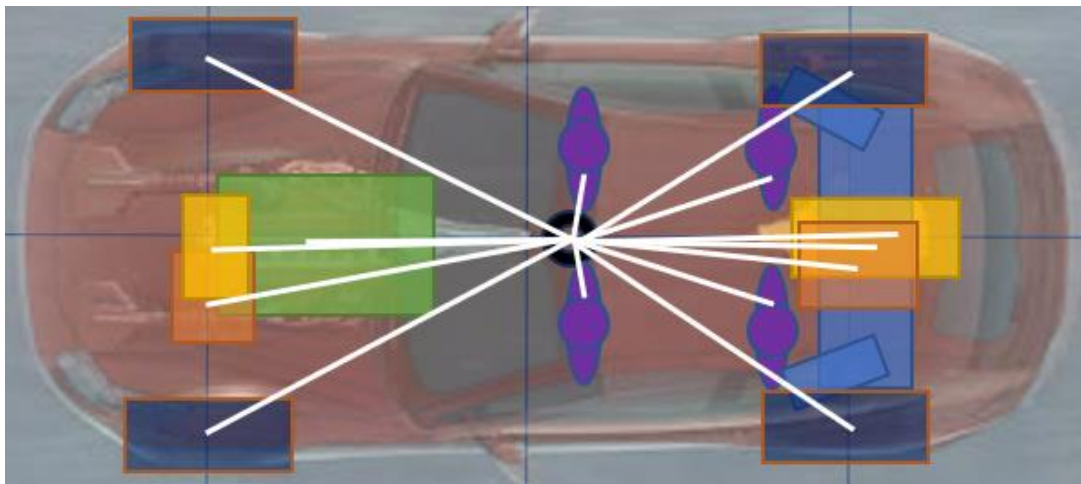


Figure 4 - Lumped mass model to find Moment of Yaw Inertia

In the model used to help calculate the Ferrari FF's moment of yaw inertia, boxes similarly used in the lumped mass model were used to replicate the position of each component. The black circle in the centre represents the longitudinal centre of gravity previously found.

All measurements to be taken from CG point			Total Wheelbase (mm)	2990				
			longitudinal CG (mm)	1587.7	(53% of 2990)			
				Distance from CG (m)	Mass (Kg)	Moment of Inertia individual (ZZ Axis) (Kg/m ²)		
Mass 1	Green Box	Engine	1.38	175	333.27			
Mass 2	Yellow Box at front	Gearbox	1.6	40	102.4			
Mass 3	Orange Box at front	Differential	1.635	50	133.66125			
Mass 4	Purple	Driver	0.3	62	5.58			
Mass 5	Purple	Front Passenger	0.3	62	5.58			
Mass 6	Purple	Rear Passenger 1	0.9	62	50.22			
Mass 7	Purple	Rear Passenger 2	0.9	62	50.22			
Mass 8	Blue	Fuel Tank	1.58	67	167.2588			
Mass 9	Yellow Box at rear	Gearbox	1.45	72	151.38			
Mass 10	Orange Box at rear	Differential	1.45	50	105.125			
Mass 11	Dark Blue	Wheel and Tyre	1.8	25	81			
Mass 12	Dark Blue	Wheel and Tyre	1.8	25	81			
Mass 13	Dark Blue	Wheel and Tyre	1.5	25	56.25			
Mass 14	Dark Blue	Wheel and Tyre	1.5	25	56.25			
						Moment of Inertia (ZZ Axis)	1379.19505	Kg/m ²

Figure 5 - Spreadsheet calculations for Moment of Yaw Inertia

The moment of yaw inertia (ZZ Axis) was found using the equation below:

$$\text{Moment of Yaw Inertia} = \sum(\text{Component Mass} \times \text{Radius of Gyration}^2)$$

$$\text{Moment of Yaw Inertia} = 1379.2 \text{ Kg/m}^2$$

Though when comparing this value to other reports which have been published in the past, this value is too low for a vehicle of this mass and size. A paper written by P.Riede has written “The reasonable correlation with total mass indicates that the total pitch inertia can be reasonably estimated from the total mass by using:”

$$I_{yt}^{cgt} = 2.56W_t - 1103$$

Where

$$I_{yt}^{cgt} = \text{Total vehicle pitch moment of inertia relative to total vehicle centroidal axis } \left(\frac{\text{Kg}}{\text{m}^2}\right)$$

$$W_t = \text{Total Vehicle Mass (Kg)}$$

Though later in the report Riede states “Sports cars tend to fall somewhat below this therefore care should be used when making estimates for those vehicles.” But thankfully states an equation to approximate the moment of yaw inertia:

$$I_{zt}^{cgt} = 2.86W_t - 1315$$

Where

$$I_{zt}^{cgt} = \text{Total vehicle yaw moment of inertia relative to total vehicle centroidal axis } \left(\frac{\text{Kg}}{\text{m}^2}\right)$$

$$W_t = \text{Total Vehicle Mass (Kg)}$$

When using Riede’s approximation for moment of yaw inertia, the value is much like other vehicles with similar total mass and wheelbase size. (Reide, Leffert, & Cobb, 1989)

$$I_{zt}^{cgt} = 2.86 \times 1880 - 1315$$

$$I_{zt}^{cgt} = 4061.8 \text{ kg/m}^2$$

Therefore, the moment of inertia used will be the 4061.8 kg/m².

$$\underline{\text{Moment of Yaw Inertia} = 4061.8 \text{ Kg/m}^2}$$

7.0 - Position of the inertial conjugate

With both the longitudinal centre of gravity and moment of yaw inertia known, the inertial conjugate can be established. Once the front wheels are turned, this applies a lateral force upon the FF which give the rear tyres a direction and magnitude, this is determined by the mass, moment of inertia and distance from the centre of gravity to the front and rear axle.

The centre of gravity will not endure any rotation but purely translation however inertial conjugate results in a linear acceleration and rotational acceleration of the Ferrari. Points below the centre of gravity have a combination of rotational acceleration adding to the linear acceleration, if it is above the centre of gravity, it will be a subtraction instead. The position of inertial conjugate is where the linear acceleration is zero.

The equations used to find the position of the inertial conjugate are below:

$$\text{Radius of Gyration}^2 = \text{Moment of Yaw Inertia} \div \text{Total mass}$$

$$\text{Inertial Conjugate} = \text{Radius of Gyration}^2 \div \text{distance between CG and front axle}$$

$$\text{Radius of Gyration}^2 = 4061.8 \div 1880$$

$$\text{Radius of Gyration}^2 = 2.161\text{m}$$

$$\text{Inertial Conjugate} = 2.161 \div 1.5877$$

$$\text{Inertial Conjugate} = \underline{1.361\text{m}}$$

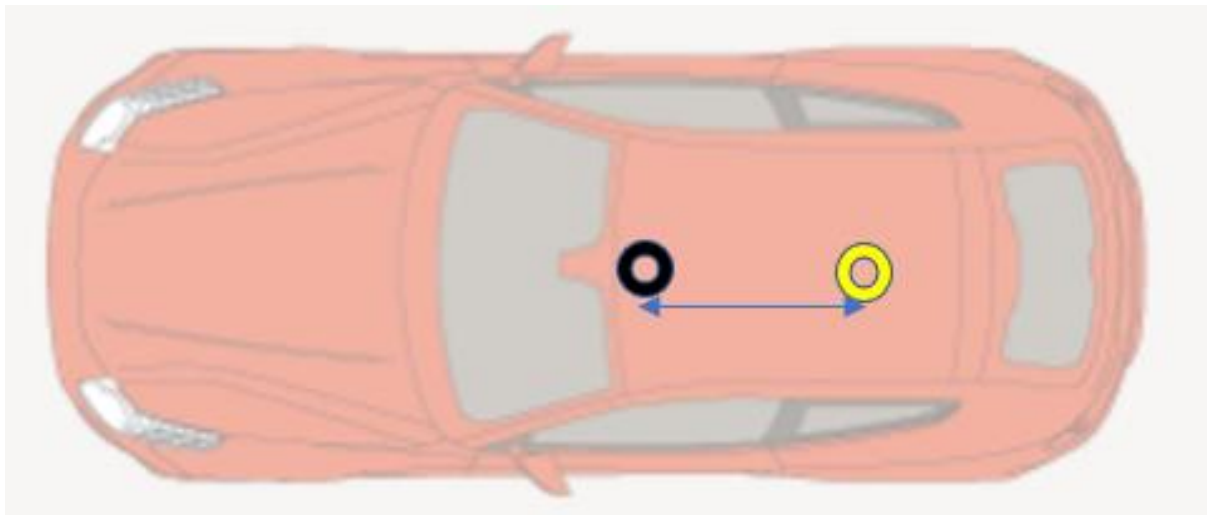


Figure 6 - 2D scan with Inertial Conjugate Distance

The inertial conjugate is 1.361m behind the longitudinal centre of gravity, this is expected due the car already having a rear bias weight distribution.

8.0 - Dynamic index of the FF

The dynamic index and the inertial conjugate are linked as it is effectively the length ratio between the distance from the CG to the rear axle against the distance from CG to the inertial conjugate. The use of the dynamic index value is to give a quick explanation of where the inertial conjugate is positioned, DI values > 1 means it is behind the rear axle and results in the rear of the car moves inwards when in lateral acceleration and reduces rear tyre slip angle, if the DI is < 1 , the opposite effect is seen.

Vehicles with lower DI values in general are more agile and nimble however can become quite twitchy and unmanageable when at speed.

$$D.I = \frac{I_{zz}}{m.a.b}$$

$$D.I = \frac{4061.8}{4010.86}$$

$$D.I = 1.012$$

The Ferrari FF's dynamic index is 1.012 from the calculations made, as assumptions have been made earlier in the report this can't be a definite value however as the vehicle is a grand tourer style vehicle, it isn't designed to be agile and nimble but is designed to be comfortable at speed on long stretches of road, however with the help of torque vectoring, both can be achieved whilst battling the fundamental values.

9.0 - Mechanical torque path to the front wheels

Within this section of the report, the front gearbox ratios were looked into to understand the mechanical torque path to the front wheels.

The front gearbox or PTU only has two gears and a reverse whereas the rear gearbox has 7 gears. The 1st gear in the 4RM is 6% taller than 2nd gear in the traditional gearbox, 2nd gear in the PTU is 6% taller than 4th gear in the traditional gearbox. In gears 5th, 6th and 7th the FF is fully rear wheel drive only as the PTU engages a neutral and has no further input to the front wheels. In the PTU, 1st gear is engaged when the FF is in either 1st or 2nd in the traditional gearbox and 2nd is engaged when in either 3rd or 4th in the rear gearbox.

The PTU can only ever send a max of 20% of the produced to the front wheels when engaged. As the Ferrari FF makes 683Nm of torque, the max the front wheels will ever see is 68.3Nm each. Due to this, Ferrari have been able to reduce the diameter of the front half shafts.

If the torque path for the front wheels was to be drawn, both drawings would look incredibly similar minus the 1st and 2nd gears within the PTU as these have different gearing to match the different ratios.

The figure below demonstrates some of the effects the PTU has with regards to gearing and torque path.

			Engine Crank Speed (RPM)	Front Wheel Clutch (RPM)	Delta Clutch Speed (RPM)																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								</
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Figure 7 - PTU/4RM gearing and torque calculations

10.0 – Clutch Packs and Axial Force

Within the 4RM front drive system there are a number of flat annular plates which are held in contact by an axial force. Each pair of contact surfaces carries the full load with each side of each plate generally effective, therefore in some cases the total torque is transmitted is 2x number of plates times the torque transmitted by one pair of contact surfaces.

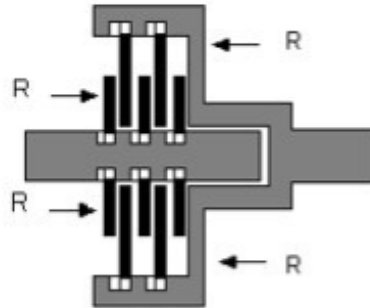


Figure 8 - Multi Pack Clutch Diagram

To calculate the axial force acting on the plates some data is first needed:

No. of plates = 6 (this can be counted in Figure **)

Outer radius (mm) = 75 (approx.)

Inner radius (mm) = 40 (approx.)

Input speed (RPM) = 3000

Coefficient of friction = 0.25

Torque max = 136.6Nm (20% of 683Nm)

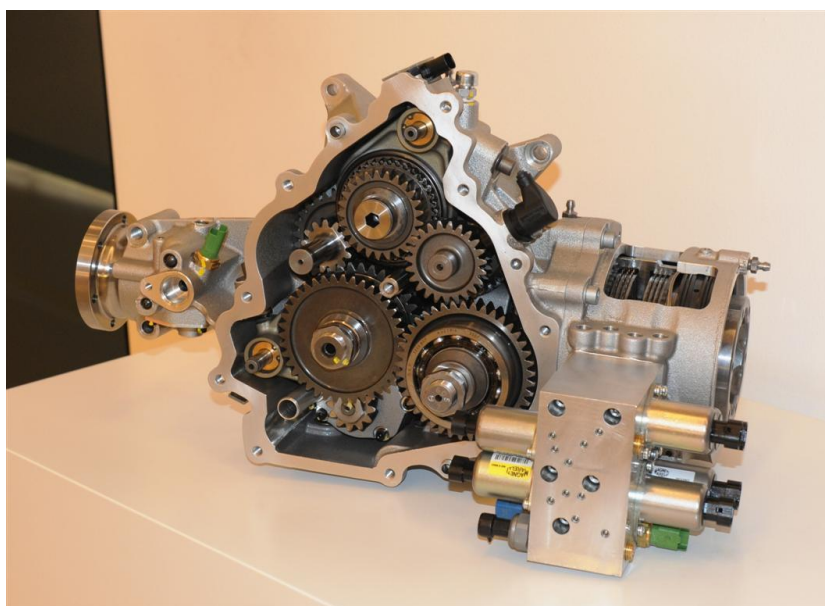


Figure 9 - Ferrari FF 4RM/PTU (Wong, 2011)

$$T_{max} = \frac{2n\mu W(r_2+r_1)}{2}$$

$$W = \frac{2T_{max}}{2n(r_2+r_1)}$$

$$W = \frac{2T_{max}}{2n(r_2+r_1)}$$

$$W = \frac{2 \times 136.6}{2 \times 6(0.075 + 0.04)}$$

$$W = 197.97N$$

The axial force acting upon the multi pack clutches is 197.97N at 20% of full engine torque. If full engine torque was to be applied, the axial force would have been 989.86N acting on the clutch.

11.0 - Potential longitudinal acceleration

The longitudinal acceleration of the Ferrari will still vary on different grip levels depending on which surface it is on, as it uses all AWD when in 4th or less, both AWD and RWD can be looked at and calculating how much help the 4RM and PTU actually is.

As Newtons 2nd Law of Force = mass x acceleration, this can be rearranged for acceleration easily.

$$Acceleration = \frac{Force}{Mass}$$

Though with varying grip levels will mean varying co-efficient of friction changing the amount of grip the FF has. As the mass does not change, the force will need to be calculated prior to using $A=F/M$.

$$a = \frac{F}{m}$$

$$F = F_{Res} - \mu mg$$

Where

μ = Coefficient of Friction (0.1 on Ice, 0.4 on Snow and 1.0 on Tarmac)

F_{Res} = Resultant Force (N) (13500N, this was found by finding acceleration from $\Delta v \div \Delta t$)

m = Mass (Kg) (1880)

Driving on Ice:

$$F = 13500 \times 0.1 \quad F = 1362.77N$$

$$a = \frac{1362.75}{1880} \quad a = 0.72ms^2$$

Driving on Snow:

$$F = 13500 \times 0.4 \quad F = 5450.98$$

$$a = \frac{5450.98}{1880} \quad a = 2.90ms^2$$

Driving on Tarmac:

$$F = 13500$$

$$a = \frac{13500}{1880} \quad a = 7.18ms^2$$

12.0 - Potential yaw rate increase that the system could generate

To establish the possible improve the torque vectoring system has on yaw rate, first a baseline must be determined.

For example, if the FF was purely RWD and was approaching a corner at 5m/s and the driver turned the handwheel 90°, the minimum diameter corner it could take would be 20m. From this statement the yaw rate can be calculated.

$$\text{Diameter} = 20\text{m}$$

$$\text{Velocity} = 5 \text{ m/s}$$

$$\text{Circumference} = \pi \times \text{Diameter}$$

$$\text{Circumference} = \pi \times 20$$

$$\text{Circumference} = 62.83\text{m}$$

$$\text{Time per "lap"} = \text{Circumference} \div \text{Velocity}$$

$$\text{Time per "lap"} = 62.83 \div 5$$

$$\text{Time per "lap"} = 12.57\text{s}$$

$$\text{Yaw Rate} = 360 \text{ deg} \div \text{Time per "lap"}$$

$$\text{Yaw Rate} = 360 \div 12.57$$

$$\text{Yaw Rate} = 28.64^\circ \text{ per Second}$$

As the Ferrari FF has torque vectoring, this makes its cornering ability greater as it can carry equal speed around a tighter radius corner, to compare the yaw rate increase possibility, the same equations will be used however using a 18m diameter corner. The benefit of this, the driver would still feel grip on turn in but will need to increase the rotation on the hand wheel to unlock that extra yaw rate now available.

$$\text{Diameter} = 18\text{m}$$

$$\text{Velocity} = 5 \text{ m/s}$$

$$\text{Circumference} = \pi \times \text{Diameter}$$

$$\text{Circumference} = \pi \times 18$$

$$\text{Circumference} = 56.55\text{m}$$

$$\text{Time per "lap"} = \text{Circumference} \div \text{Velocity}$$

$$\text{Time per "lap"} = 56.55 \div 5$$

$$\text{Time per "lap"} = 11.31\text{s}$$

$$\text{Yaw Rate} = 360 \text{ deg} \div \text{Time per "lap"}$$

$$\text{Yaw Rate} = 360 \div 11.31$$

$$\text{Yaw Rate} = 31.83^\circ \text{ per Second}$$

With torque vectoring equipped, the FF has a larger yaw rate which allows to take corners at a faster speed, the delta yaw rate is 6.19° per second which on top of increased launch speed from a stand still gives the FF a good advantage compared to if it was just RWD.

13.0 - Possible control algorithms, sensors required and potential vehicle dynamic improvements

To create a control algorithm for a torque vectoring system would need to consider where and what the vehicle is doing as well as what the driver inputs are depending on whether that is accelerating, decelerating or cornering. Some of the possible inputs and relevant sensors have been discussed.

As the differentials main job is to distribute torque to the drive wheels, knowing what speed they are already rotating at is crucial, if there is an unbalance along an axle and equal torque is supplied to each wheel, a moment will be created around the longitudinal CG from the wheel with the greater speed, this is also the same as when the vehicle will drive across a surface with varying co-efficient of friction, altering the grip level of the tyres. Using a system the same as an ABS unit with a trigger wheel should be able to measure both wheel speeds.

The vehicle speed is as important if not more important than wheel speed as without knowing vehicle speed, some great errors can appear. An example of this would be if all drive wheels did not have sufficient traction and begin to spin, the wheel speed would be much greater than the vehicle speed, if the wheels continue to spin and the tyres very quickly gain traction, the possibility of failure to a mechanical part would be high. To measure vehicle speed can be difficult so the use of multiple sensors such as a GPS and radar system could be looked into.

Yaw pitch and roll Knowing whether the vehicle is in yaw, pitch or roll or a combination of the three would be needed to know which wheel is going to be under max load and therefore sending available torque to the opposing wheels. Measuring where the car is in its 3 axis can be measured by an tri axial accelerometer, this can also measure the rate of change of yaw, pitch and roll indicating to the system if the car is performing a fast manoeuvre as well as being tied into measure accelerator position and handwheel position, the system will be able to see the trend of how the driver has been operating the vehicle, this can be seen as erratic and rapid changes in accelerator, brake and hand wheel position.

14.0 - Conclusion

To conclude the report, The Ferrari's 4RM niche design is the first of its kind to come from Ferrari. It was still built on the well-known front rear architecture with the engine mounted in the middle, the engine was fully behind the front axle. The crankshaft had two outputs, one for the traditional prop-shaft into the rear mounted 7 speed gearbox whilst the other output went into the Power Transfer Unit which has its own 2 speed gearbox and two wet multi-plate clutches. This allowed the FF to have all wheel drive as well as torque vectoring.

Though the front wheels can only take a maximum of 20% of the total torque produced, the packaging of the 4RM and PTU allows both the sized well and lightweight weighing roughly half the weight of a traditional AWD system.

The positives of the system would be it allows for the FF to have improved acceleration from a launch and improved cornering ability whilst keeping a lower centre of gravity with the light and compact AWD system.

The negatives would be it has limited torque to the front wheels at 20% and is only engaged until 4th gear in the traditional gearbox. The other negatives would be within the report and the calculations themselves; a lot of assumptions were made to not being able to access data on the FF as Ferrari are known to be secretive with fine details, without having a physical test piece, some measurements were not as accurate as they could have been though gave realistic answers which should be expected from a vehicle of this category.

15.0 - Bibliography

- AdjustMyCar. (2013, 01 01). *How much does a car engine weigh*. Retrieved from AdjustMyCar: <https://adjustmycar.com/how-much-does-a-car-engine-weigh/#:~:text=How%20Much%20Does%20a%20V12,to%2090%C2%B0%20as%20we ll.>
- Car and Driver. (2018, 04 09). *Explained: How To Measure a Vehicle's Center-of-Gravity Height*. Retrieved from Car and Driver: <https://www.caranddriver.com/news/a18201745/explained-how-to-measure-center-of-gravity-height/>
- Cottingham, D. (2015, 04 24). *Why does burning 1 litre of fuel create over 2kg of carbon dioxide?* Retrieved from Driver Knowledge Tests: <https://www.driverknowledgetests.com/resources/why-does-burning-1-litre-of-fuel-create-over-2kg-of-carbon-dioxide/#:~:text=One%20litre%20of%20petrol%20weighs,it%27s%20a%20potent%20greenhouse%20gas.>
- Ferrari. (2011, 01 01). *Ferrari FF*. Retrieved from Ferrari: <https://www.ferrari.com/en-EN/auto/ff>
- Hirons, R. (2022, 02 24). *Torque Vectoring Explained*. Retrieved from Carwow: <https://www.carwow.co.uk/guides/glossary/what-is-torque-vectoring#gref>
- Outlines. (2011, 01 01). *2011 Ferrari FF Hatchback blueprint*. Retrieved from Outlines: <https://getoutlines.com/vector-drawings/71/2011-2016-ferrari-ff-drawings>
- Reide, P., Leffert, R., & Cobb, W. (1989). *Typical Vehicle Parameters for Dynamic Studies Revised for the 1980's*. SAE International.
- Rettner, R. (2013, 05 30). *The Weight of the World: Researchers Weigh Human Population*. Retrieved from Live Science: [https://www.livescience.com/36470-human-population-weight.html#:~:text=The%20average%20body%20mass%2C%20globally,178%20pou nds%20\(80.7%20kg\).](https://www.livescience.com/36470-human-population-weight.html#:~:text=The%20average%20body%20mass%2C%20globally,178%20pou nds%20(80.7%20kg).)
- Shah, V. (2020, 11 08). *Torque vectoring explained*. Retrieved from CarExpert: <https://www.carexpert.com.au/car-news/torque-vectoring-explained>
- SLG. (2021, 04 22). *DCT Bible, Chapter 2 - Transmission Hardware*. Retrieved from Seems Legit Garage - SLG: <https://www.seemslegitgarage.com/post/dct-bible-chapter-2-transmission-hardware>
- Wong, J. (2011, 08 16). *LAUNCH: Ferrari FF Touches Malaysian Soil!* Retrieved from Wemotor: <https://www.wemotor.com/blog/2011/08/launch-ferrari-ff/>